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An overview of recent research on AM and OAM of wind turbine noise

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An overview of recent research on AM and OAM of wind turbine noise

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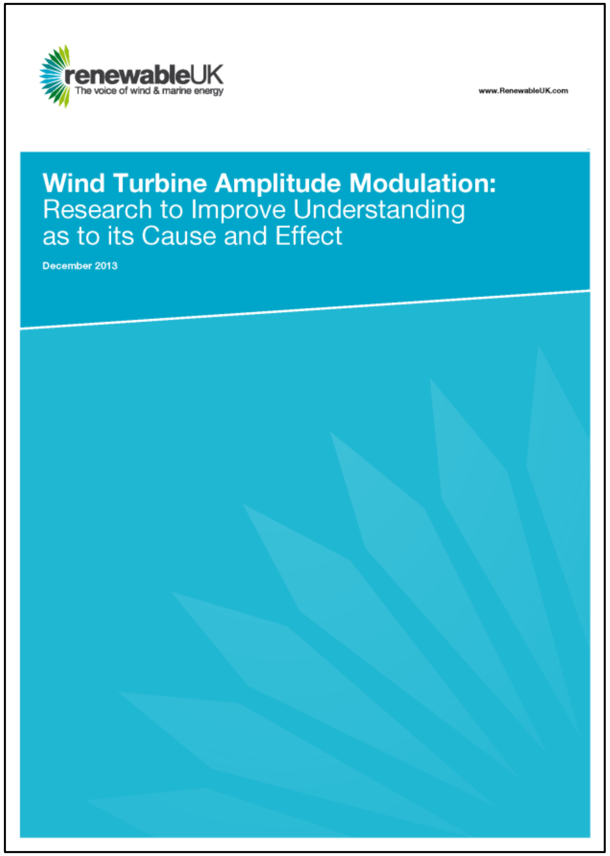
Introduction

A comprehensive research project:

" Wind Turbine Amplitude Modulation: Research to Improve Understanding as to its Cause and Effect"

coordinated and funded by Renewable UK

- carried out in the period 2010-2013
- final report released in December 2013
- DTU involved in last part



Bullmore A, Cand M, Oerlemans S, Smith MG, White P, von Hünerbein S, King A, Piper B, et al.. ReneawableUK. Wind Turbine Amplitude Modulation: Research to Improve Understanding as to its Cause and Effect. RenewableUK, United Kingdom;2013.

Madsen HAa, Fischer A, Abildgaard K. **Phase 2**, Mechanisms and causes of Amplitude Modulation (AM) and Other Amplitude Modulation (OAM) of aero-acoustic wind turbine noise. Report DTU Wind Energy I-0095 (EN), DTU Wind Energy August 2013. In RenewableUK 2013 report: Wind Turbine Amplitude Modulation: Research to Improve Understanding as to its Cause & Effect.

DTU background for conducting the AM research in the Renewable UK study

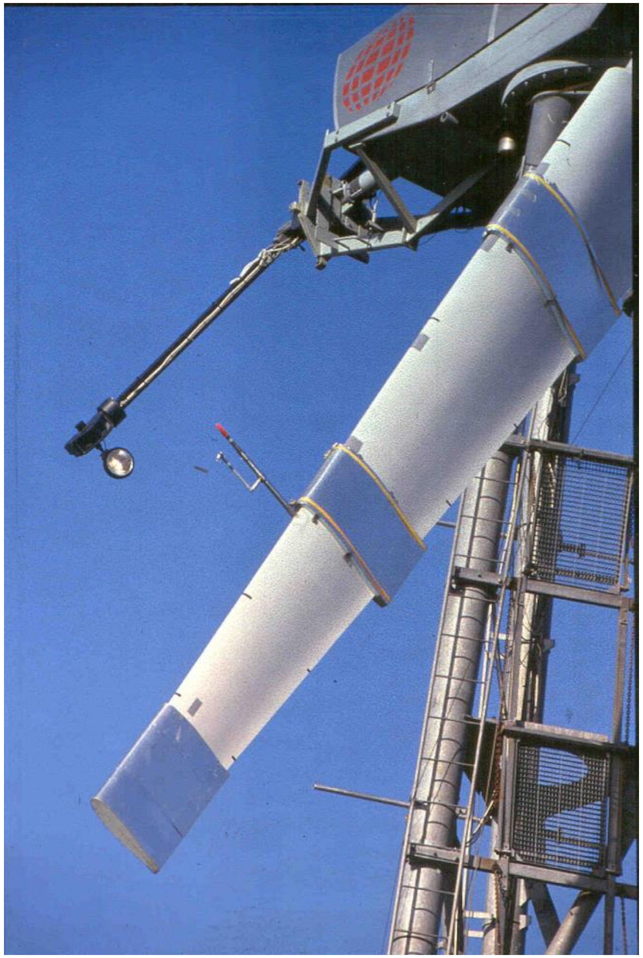
Expertise on:

- inflow measurements on a blade (since 1987)
- noise source measurements with microphones on the blade surface (since 2006)
- these techniques applied in The DAN-AERO project 2007-2010*
- rotor noise modeling
- modeling wind turbine aeroelasticity and control

* The DANAERO project was conducted in corporation between Vestas, Siemens, LM, DONG Energy and DTU Wind Energy in 2007-2010. Funded by the Danish Ministry of Energy

Inflow measurements

First measurements on a 100 kW turbine in the period from 1987-1993



Mechanism of amplitude modulation (AM) of noise – from the Ren. UK study

- caused by 1p variations of the level of trailing edge noise and change in directivity during blade rotation
- variation of a few dB over one blade revolution

Measured about 50 m upwind from a 93-m diameter pitch-controlled wind turbine

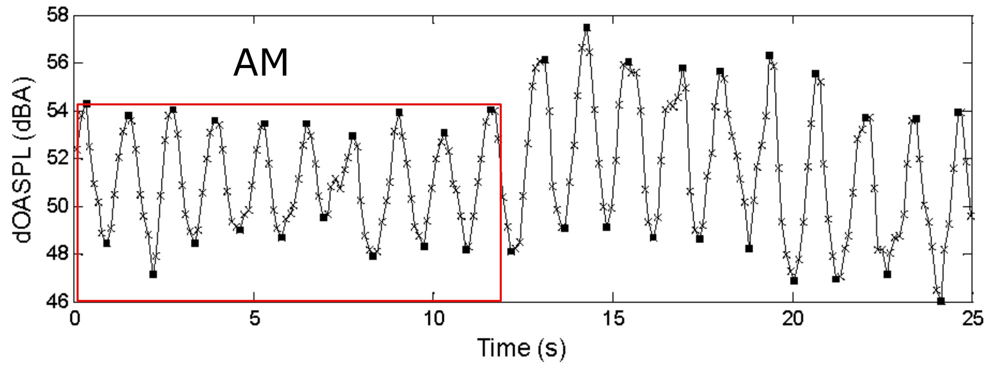


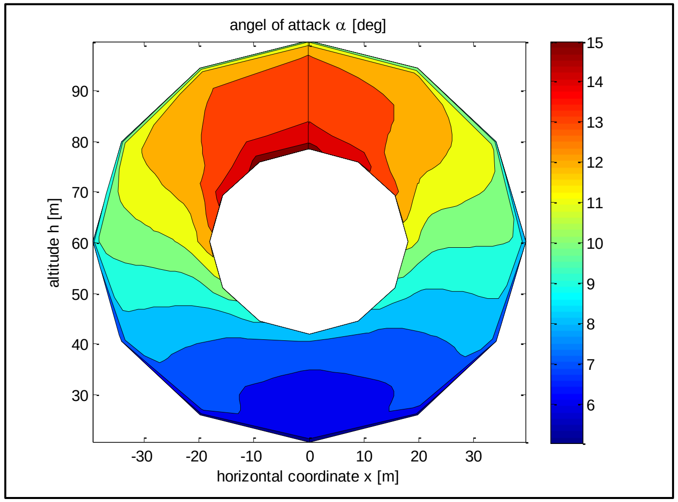
Figure 4: Time history of A-weighted overall sound level as a function of time (absolute levels not meaningful). The transition between normal swish and EAM occurs between 11 s and 13 s. The crosses indicate the instantaneous levels (averaged over 0.23 s), the squares indicate the maxima and minima.

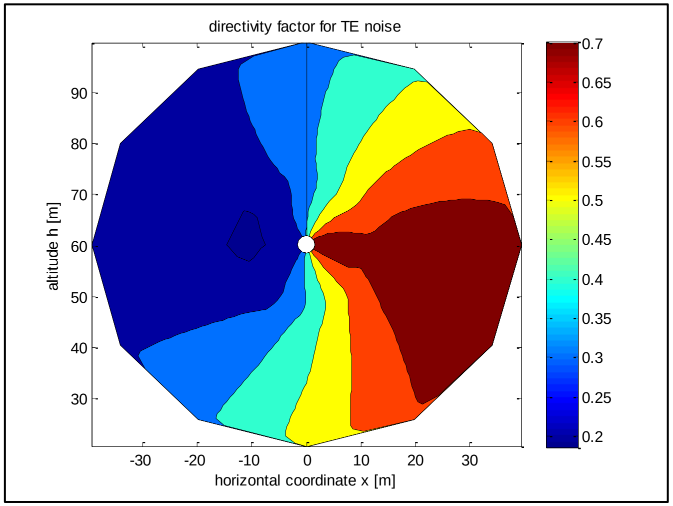
Bullmore A, Cand M, Oerlemans S, Smith MG, White P, von Hünerbein S, King A, Piper B, et al.. ReneawableUK. Wind Turbine Amplitude Modulation: Research to Improve Understanding as to its Cause and Effect. RenewableUK, United Kingdom;2013.

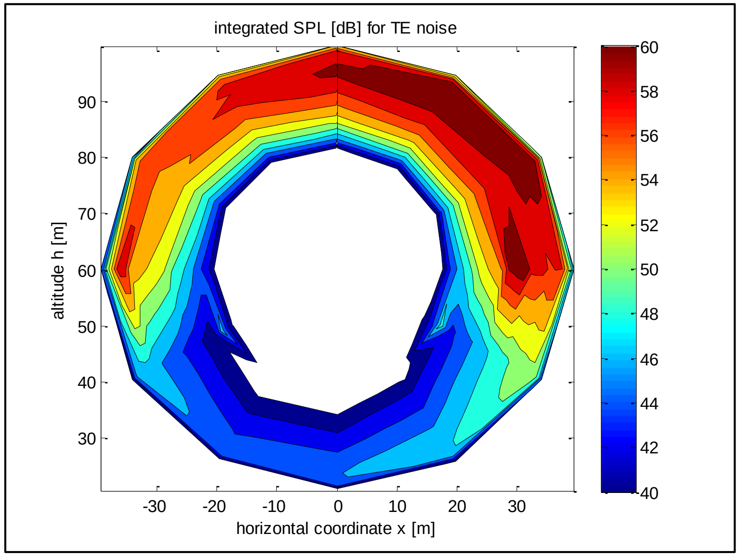
AM simulation - Shear exponent 0.2

AOA variation causing TE noise variation

Directivity for TE noise







Characteristics of extreme AM - also called EAM or OAM

- the modulation depth significantly greater than that of normal **blade swish (AM)**
- modulation depths up **to 10 dB** have been measured
- increased level at frequencies below 400 Hz
- the effect is generally strongest in the **downwind direction**

Figures from Renewable UK study on AM and OAM (EAM), December 2013

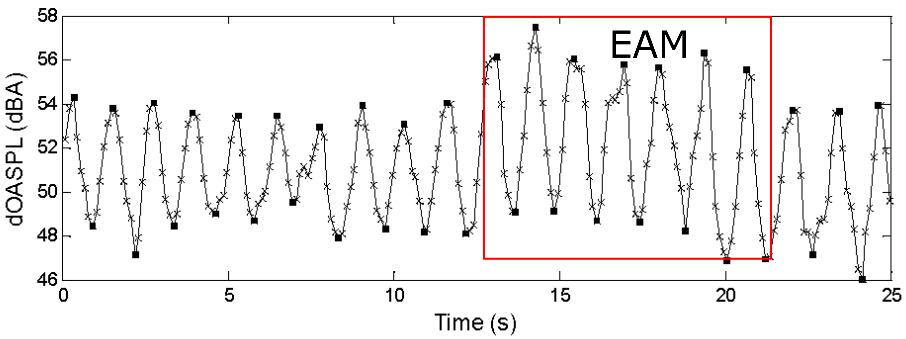


Figure 4: Time history of A-weighted overall sound level as a function of time (absolute levels not meaningful). The transition between normal swish and EAM occurs between 11 s and 13 s. The crosses indicate the instantaneous levels (averaged over 0.23 s), the squares indicate the maxima and minima.

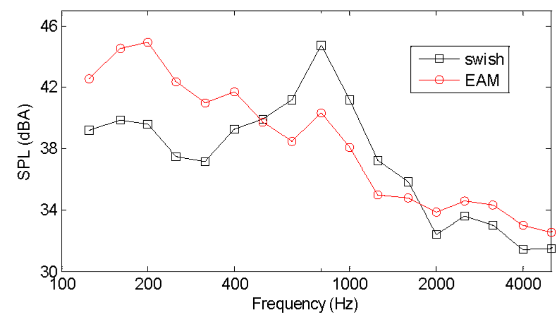


Figure 6: Average spectra for swish period and EAM period (absolute levels not meaningful). The EAM sound has much more low-frequency content than the swishing sound.

Characteristics of extreme AM - also called EAM or OAM

Normal AM

- ❑ commonly termed ‘blade swish’
- ❑ part of normal WTN
- ❑ ~5dB modulation at source
- ❑ dominant crosswind effect
- ❑ decreases away from source
- ❑ dominated by mid frequencies (400Hz to 1000Hz) ‘swish’
- ❑ source mechanism understood

Jeremy Moon, RES, 2014

OAM

- ❑ more impulsive ‘thump’
- ❑ atypical, intermittent
- ❑ >5dB (>10dB) amplitude at times?
- ❑ audible/noticeable at large distances downwind to >1km?
- ❑ additional lower frequency content (200 Hz to 500 Hz)? ‘whooomp’
- ❑ source mechanism?

Causal factors raised in the Renew. UK AM and OAM study

- ❑ OAM due to transient stall ?

- ❑ is it possible that transient stall occurs on a pitch regulated turbine in normal operation ?

- ❑ characteristics of angle of attack (AoA) variations on a real full scale turbine ?

- ❑ stall noise characteristics ?

- ❑ the causes of variability of the occurence of OAM ?

- ❑ is there a scaling effect ?

Limits of the present overview

- the noise source characteristics of AM and OAM

But many other important subjects related to AM and OAM

- identification of all important factors influencing mechanisms behind AM and OAM
- propagation effects
- quantification of AM and OAM
- annoyance characteristics of AM and OAM
- mitigation

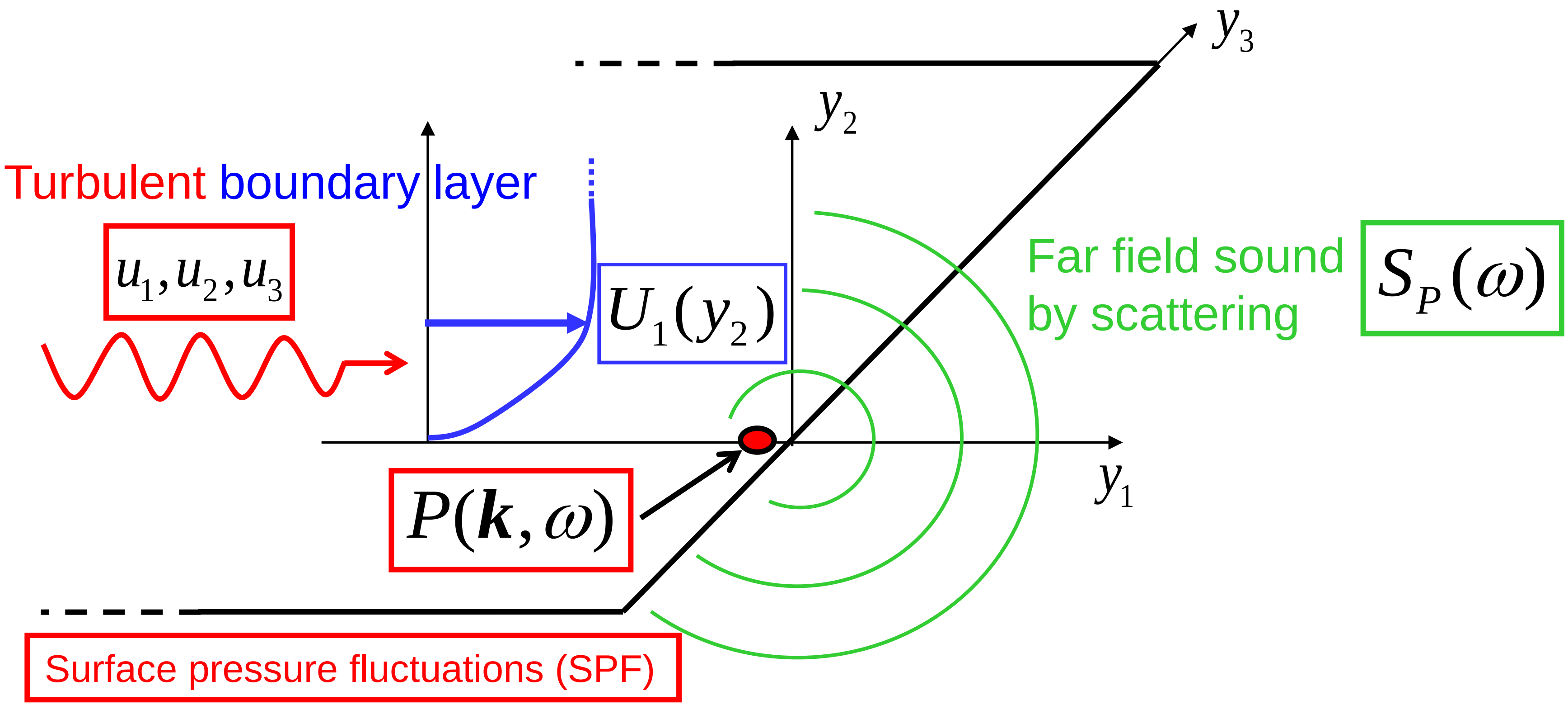
Outline

- the noise sources in relation to AM and OAM
- the measurement techniques
  - inflow – (AoA and magnitude of the relative velocity)
  - high frequency surface pressure measurements
  - measurements on full scale turbines
- results from two experimental data sets
- scaling effect and blade leading edge degradation
- conclusions

Noise sources behind AM and OAM

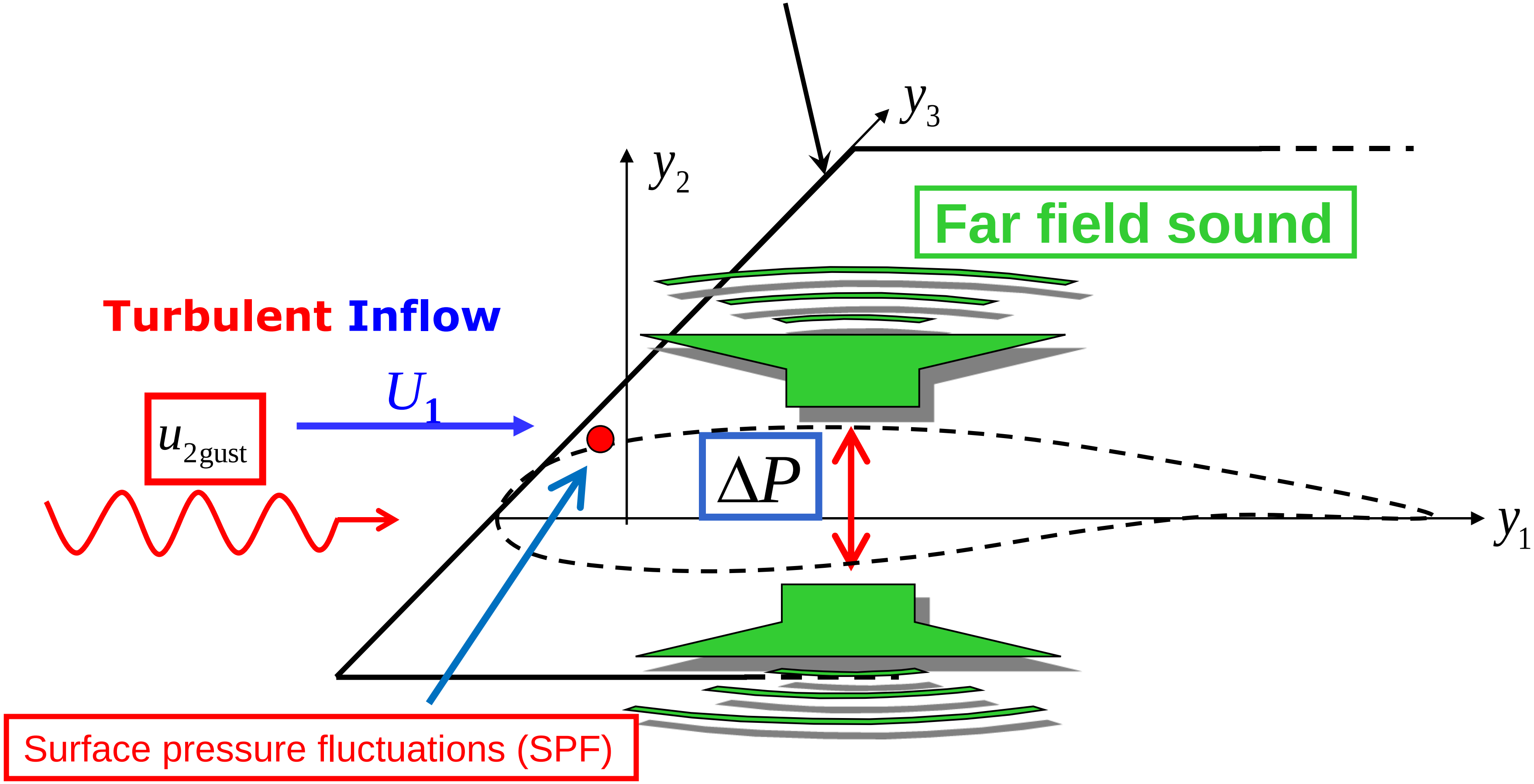
- Trailing edge (TE) noise
  - important for AM, (OAM ?)
- Stall (ST) noise
  - important for OAM
- Turbulent inflow (TI) noise
  - important for AM ? and OAM ?

TE Noise Mechanism

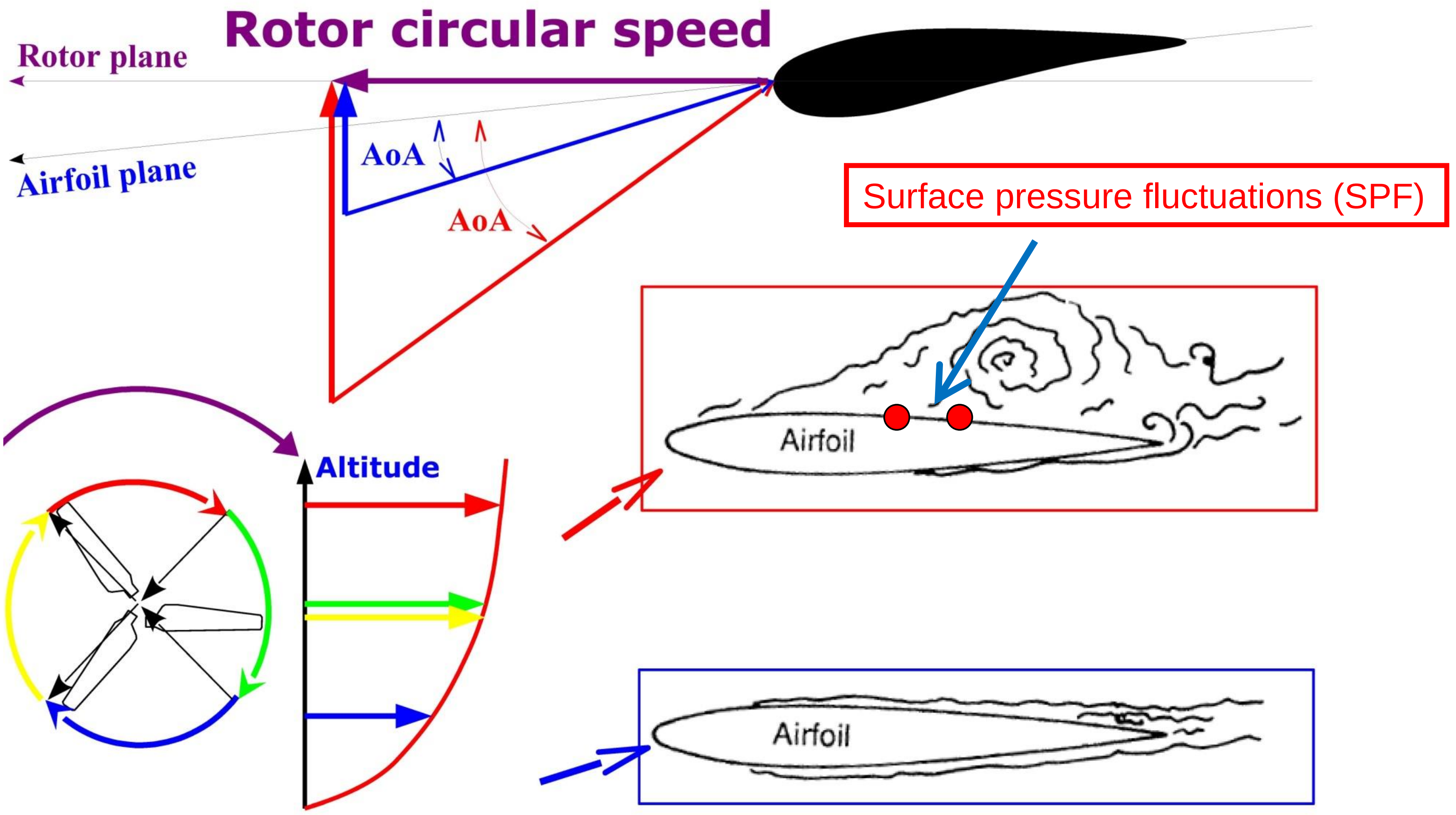


Turbulent Inflow (TI) Noise

Idealized Airfoil as an Half-Plane



Stall (ST) noise



Experimental characterization of the TE, TI and ST noise sources

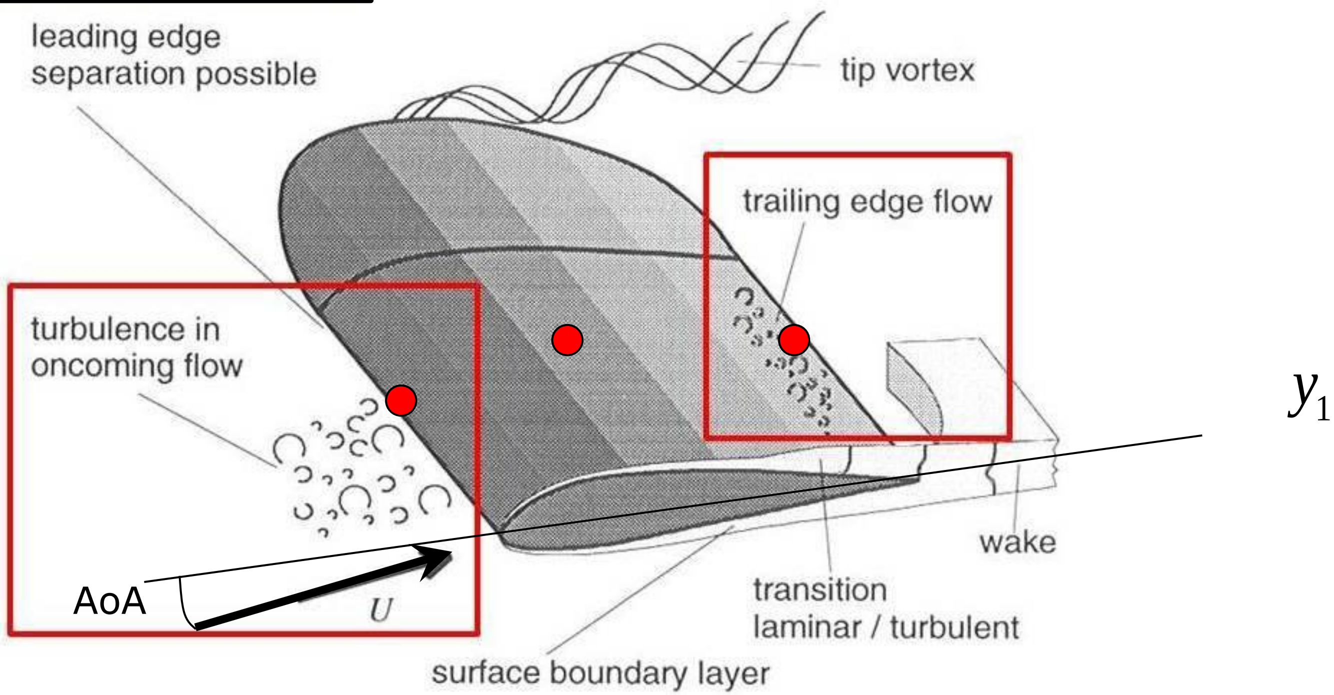
and

the measurement techniques

Experimental characterization of the source of TE, TI and ST noise

Five hole pitot tube to measure magnitude and direction (AOA) of U

Surface microphones ● to measure SFP



What are the noise sources influenced by ?

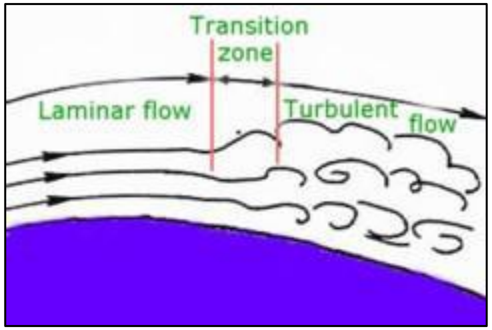
TE noise > function(AOA, U, blade roughness, transition, vortex generators)

- AOA function (inflow turbulence and shear, blade elastic torsion, blade pitch)

TI noise > function(U, inflow turbulence and shear, leading edge geometry, AOA ?)

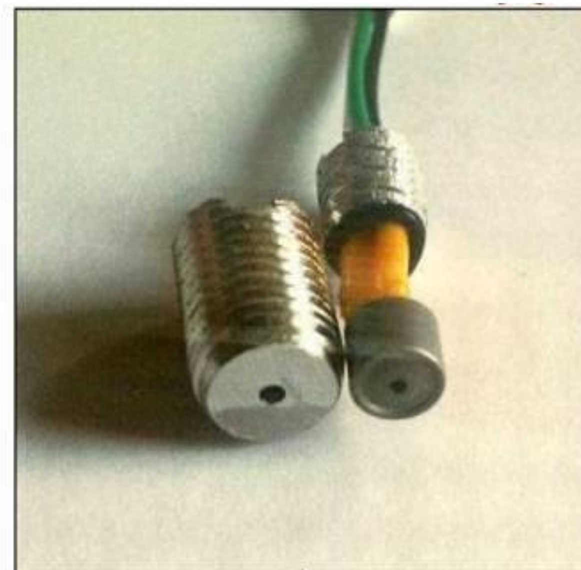
ST noise > function(AOA, U, blade roughness, transition, vortex generators)

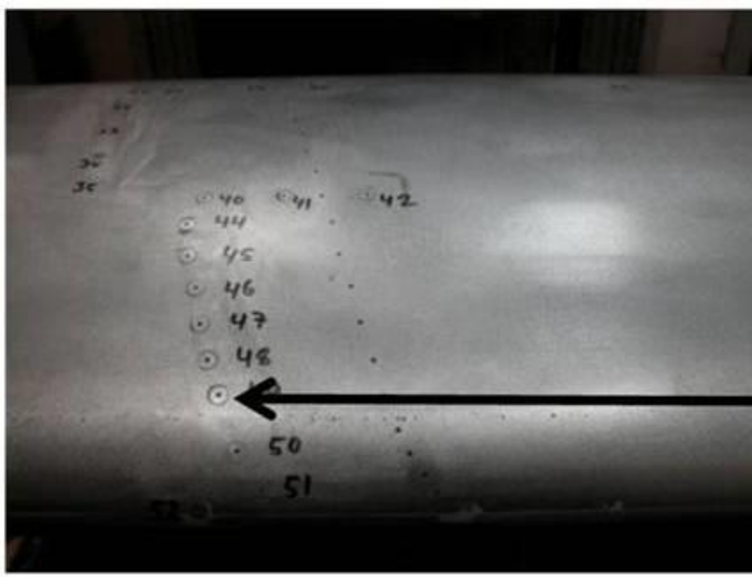
- AOA function (inflow turbulence and shear, blade elastic torsion, blade pitch)

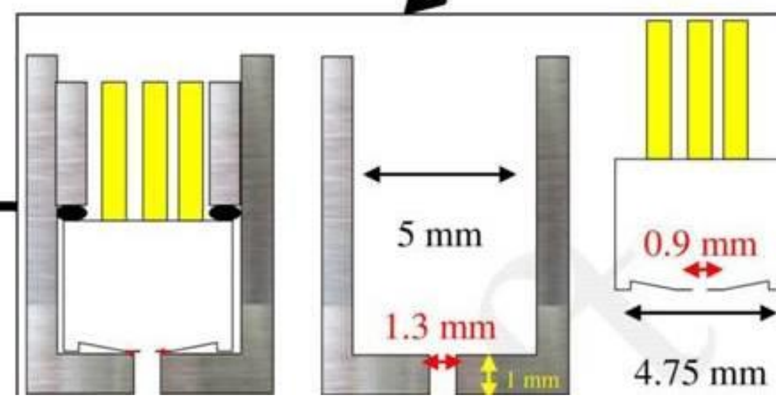


Measurement of SPF with microphones mounted on the blade

Flush-mounted HF microphones

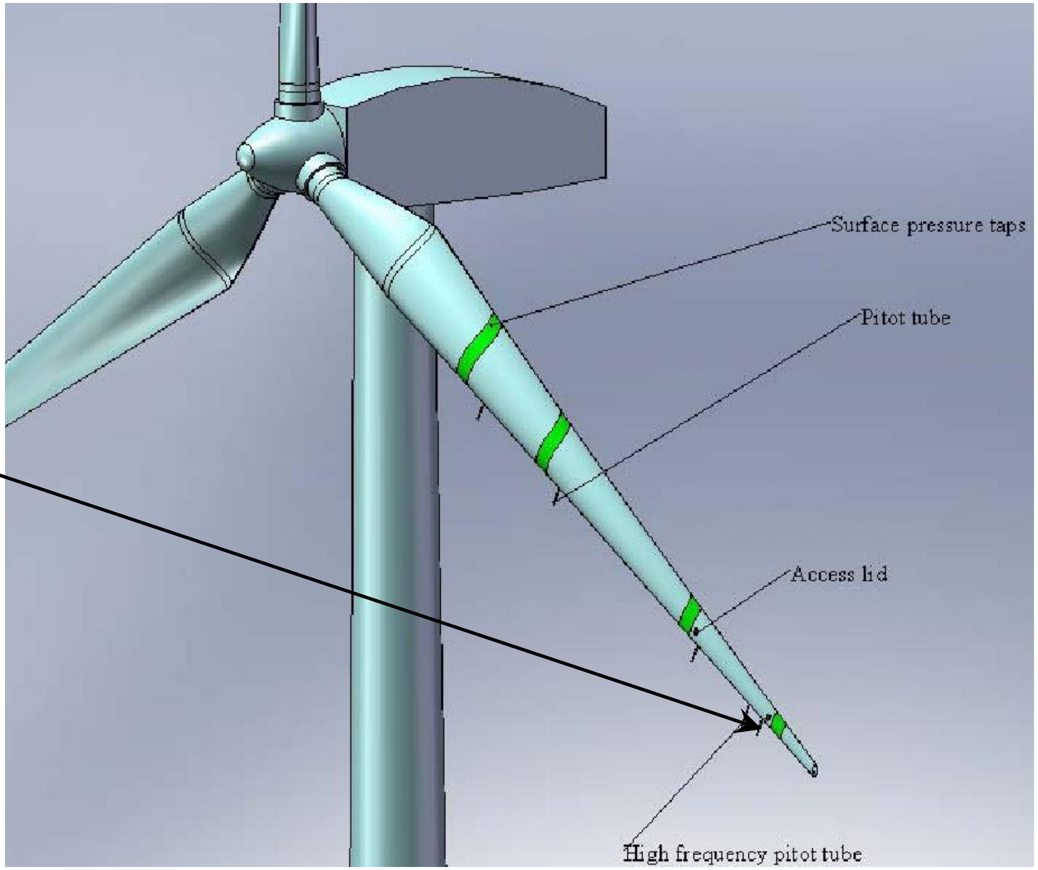






Measurement on a full scale rotor blade, 80m rotor, 2MW turbine - - DANAERO MW project 2009

- surface pressure and inflow with five hole pitot tubes measured at 4 radial stations
- **60 flush mounted microphones for high frequency surface pressure measurements**
- measurement campaigns from June to September 2009

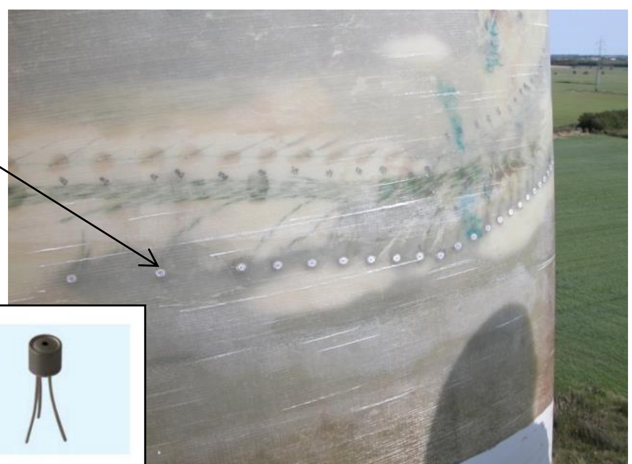


Madsen HAa et. al. , The DANAERO MW Experiments, paper AIAA 2010-645 presented at 48th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition, 4 - 7 January 2010, Orlando, Florida

Installation of the 38.8m instrumented blade in May 2009

A new test blade was manufactured and instrumented

Microphone holes



Measurement of inflow (AOA) with a five hole pitot

One pitot tube on the Siemens 3.6 MW turbine

4 pitot tubes on the 80m, 2MW, NM80 turbine

The DANAERO MW experiment 2009

Experimental data sets

1. High frequency surface pressure data correlated with inflow (AoA) data measured on an **80m diameter wind turbine rotor** – the DANAERO experiment in 2009

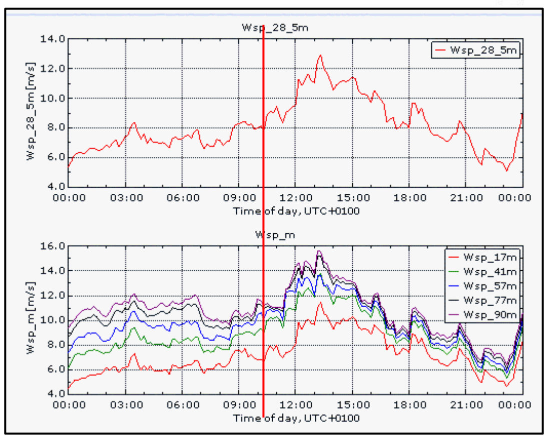
    - provides insight into change of noise source characteristics at transition from attached flow to separated flow (stall)

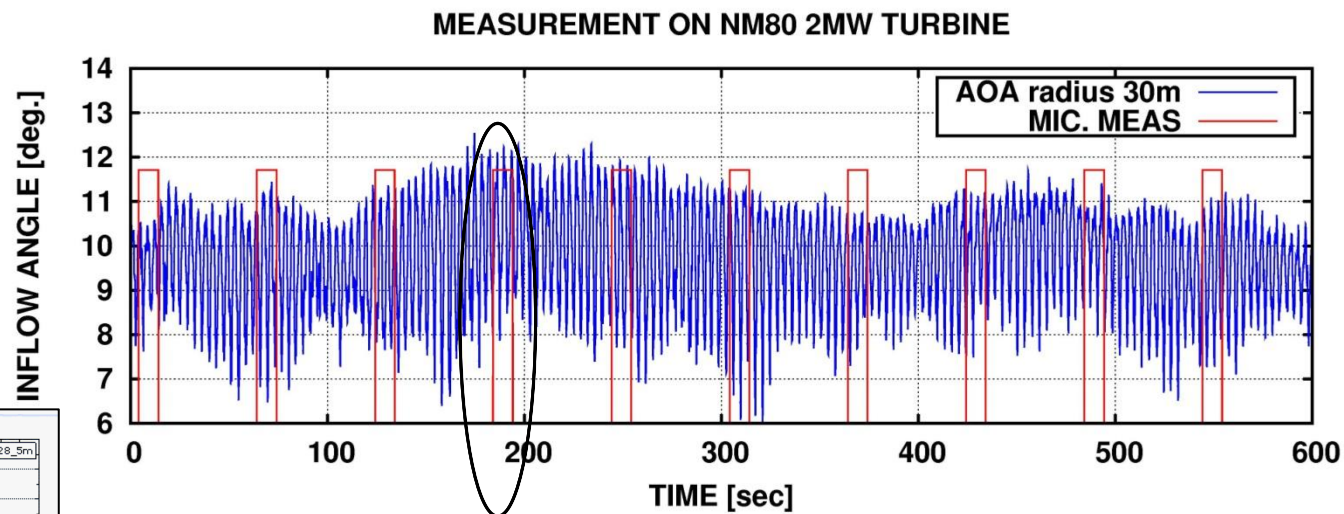
2. Measurement of inflow (AoA) on the rotating blade over three weeks on the same **turbine in 2003**

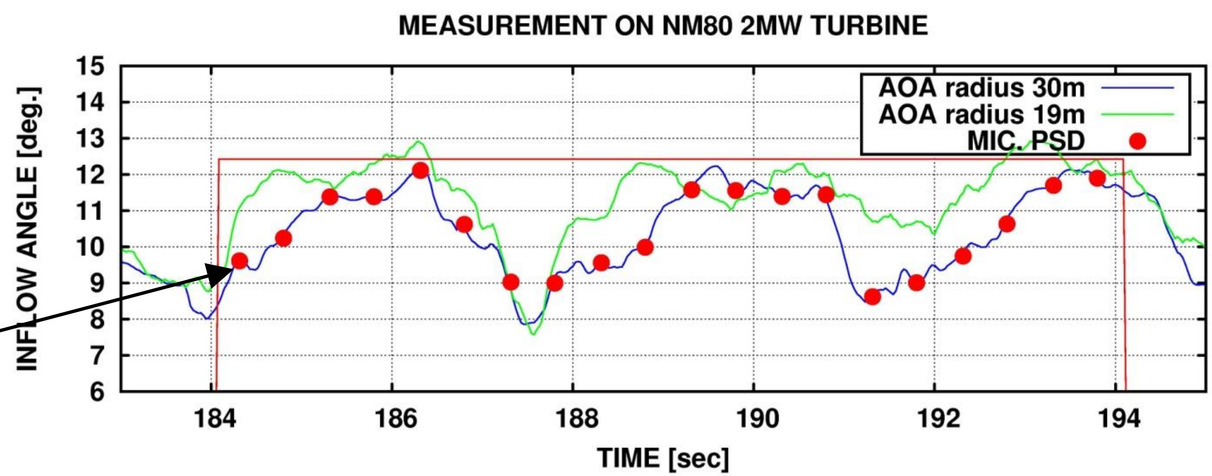
    - provides statistics on the occurrence of high angle of attack (stall) on a wind turbine in normal operation – (2014 study)

1. Measurement of SPF on a full scale rotor blade, 80m diameter rotor, 2MW

Wind shear measured in the met mast

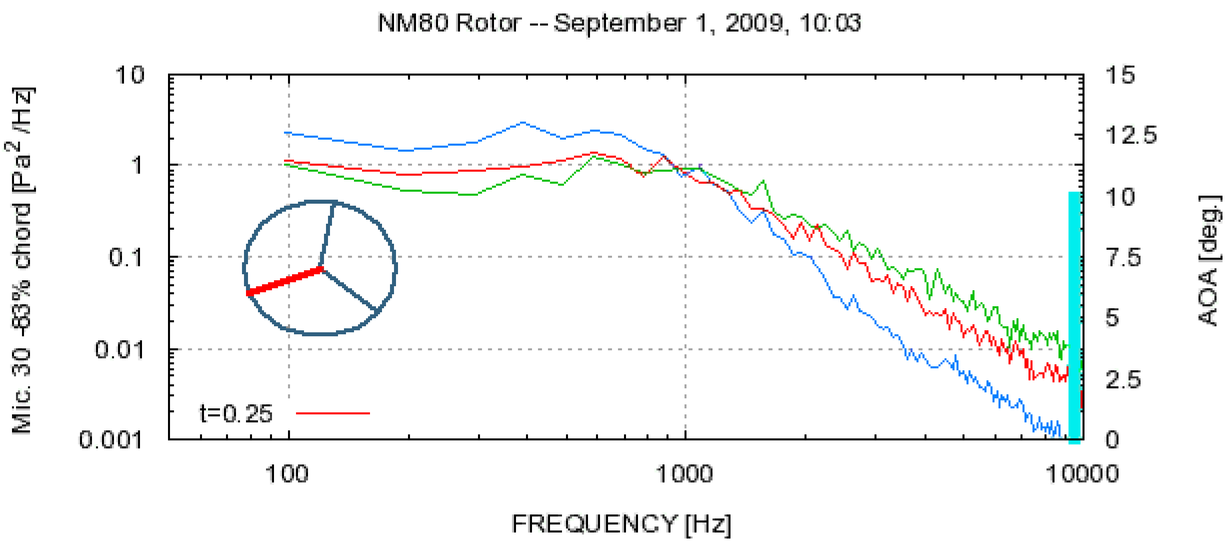






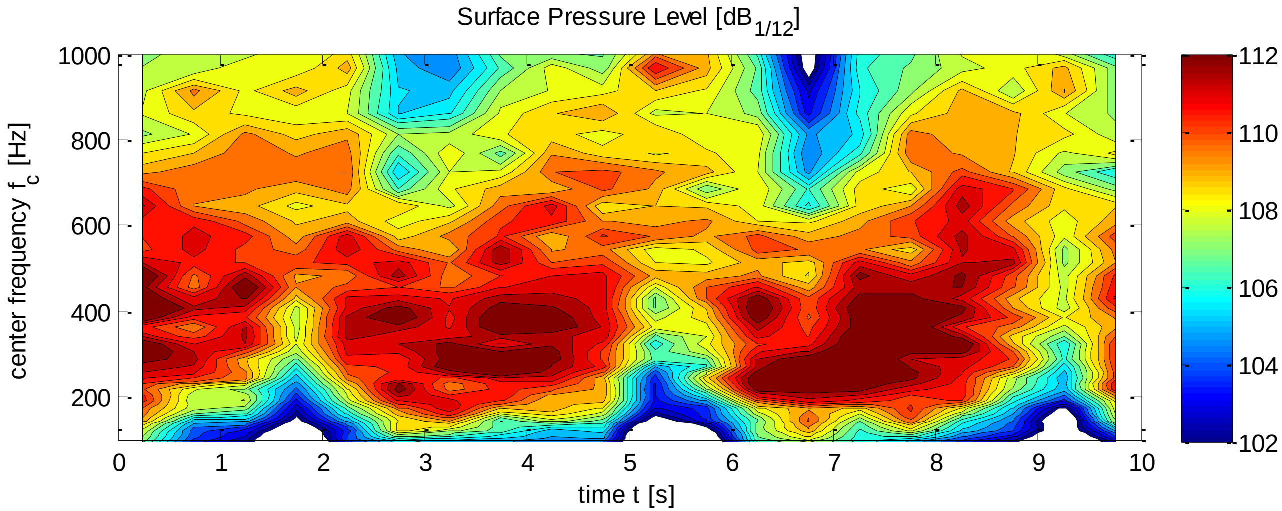
SPF spectra derived at each red dot

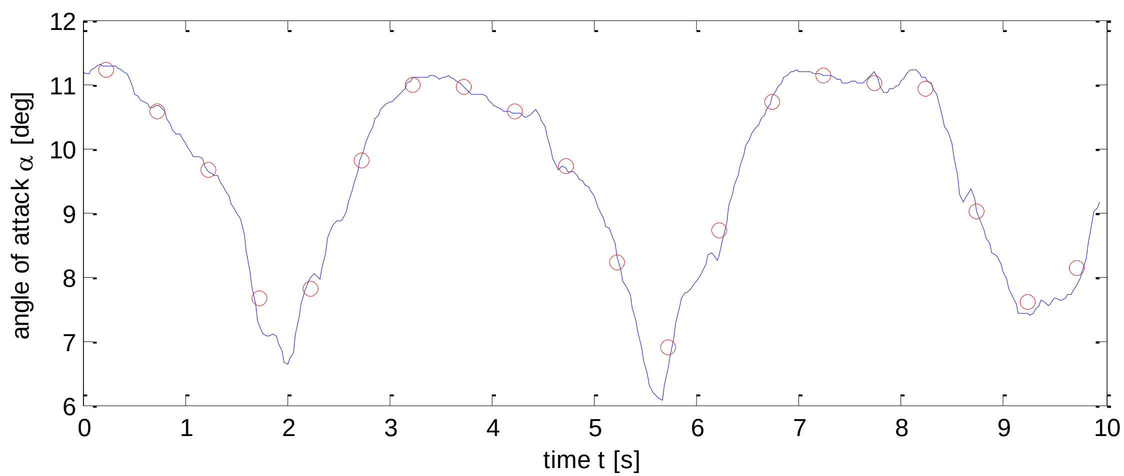
TE spectra measured during free inflow at 9-11m/s -- amplitude modulation



Each spectrum is based on 0.5sec

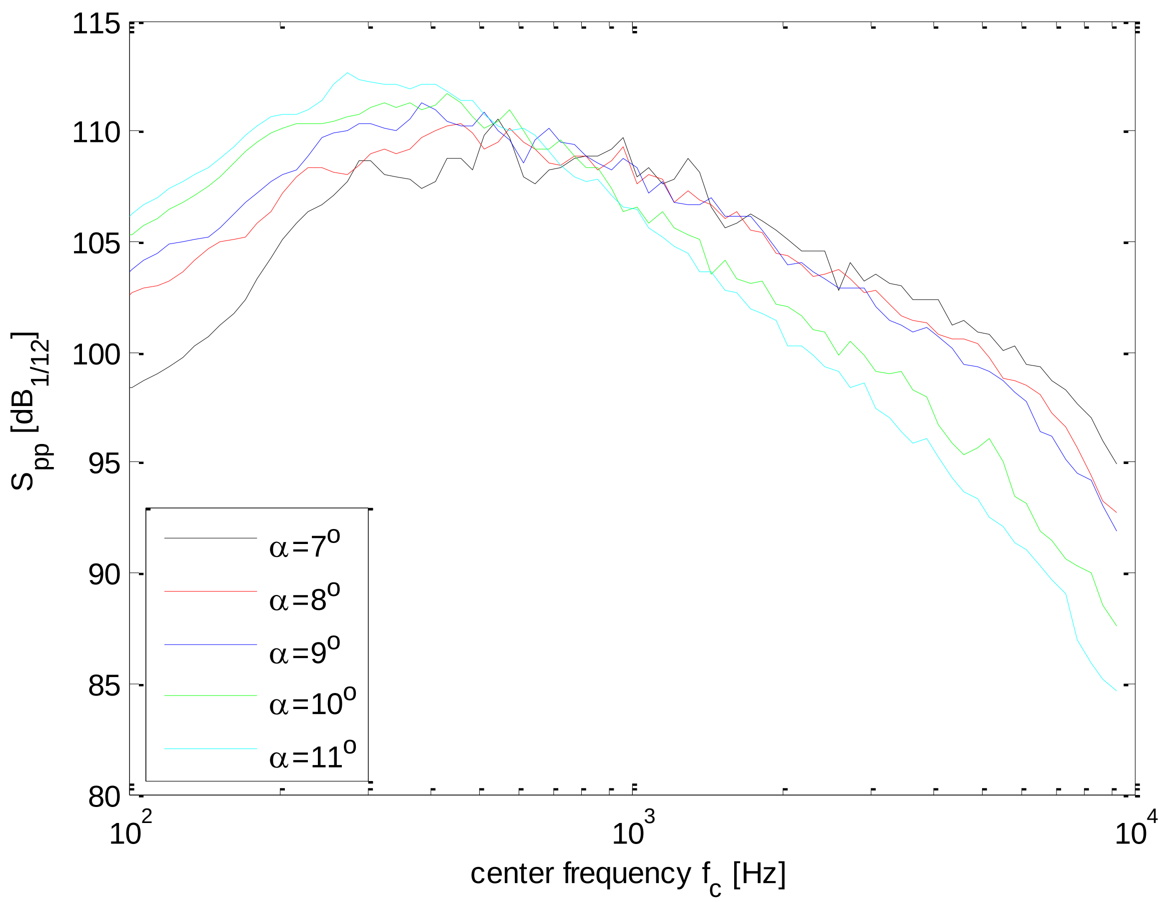
Surface pressure level on suction side at x/c=0.84, Sept 1, 2009, 10:05





Below stall

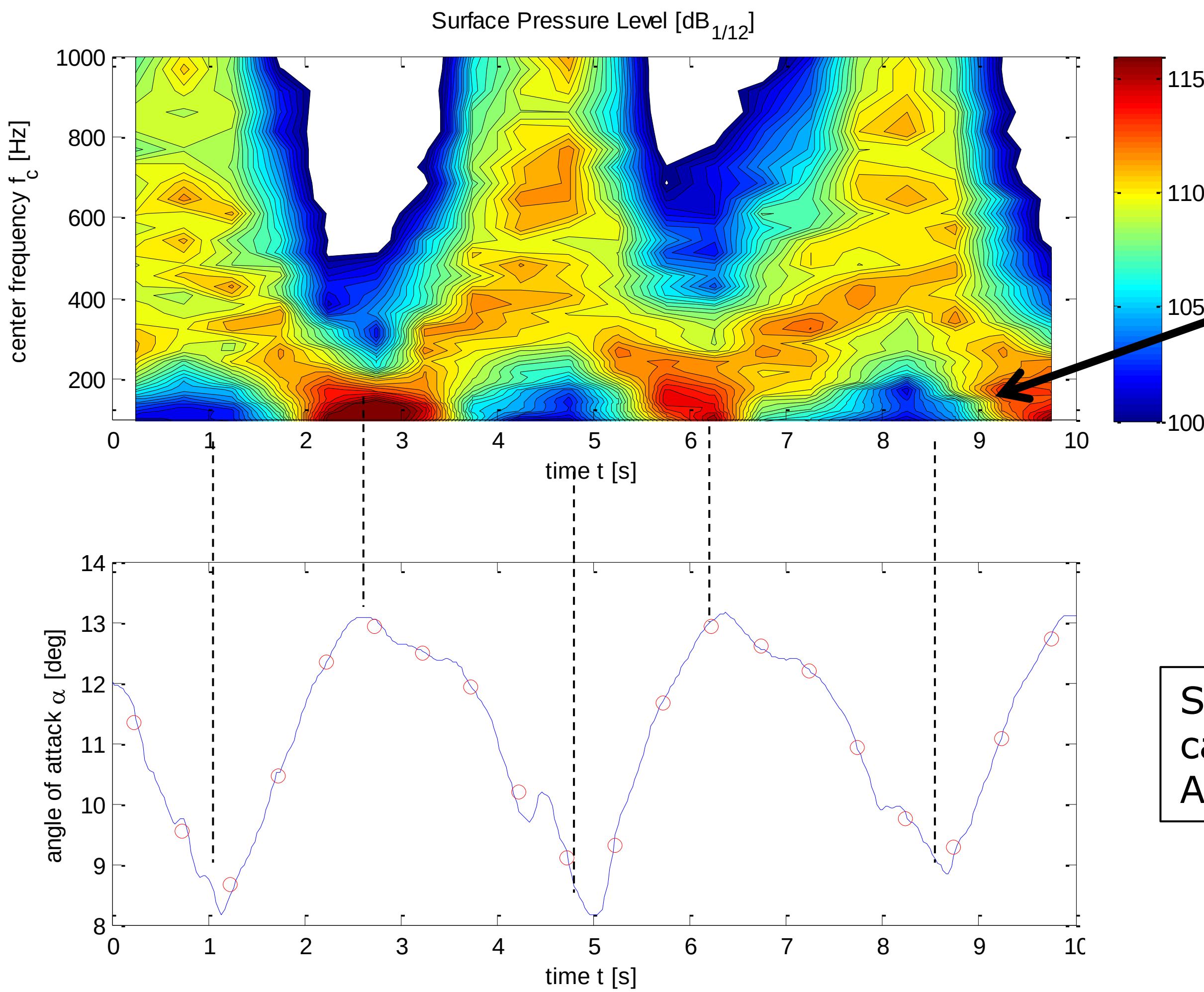
Surface pressure level on suction side at x/c=0.84, Sept 1, 2009, 10:05 binned on AoA



Below stall

DANAERO – NM80 turbine

- forced operation at high angle of attack (AOA) by negative pitch and constant rpm – **transient stall**

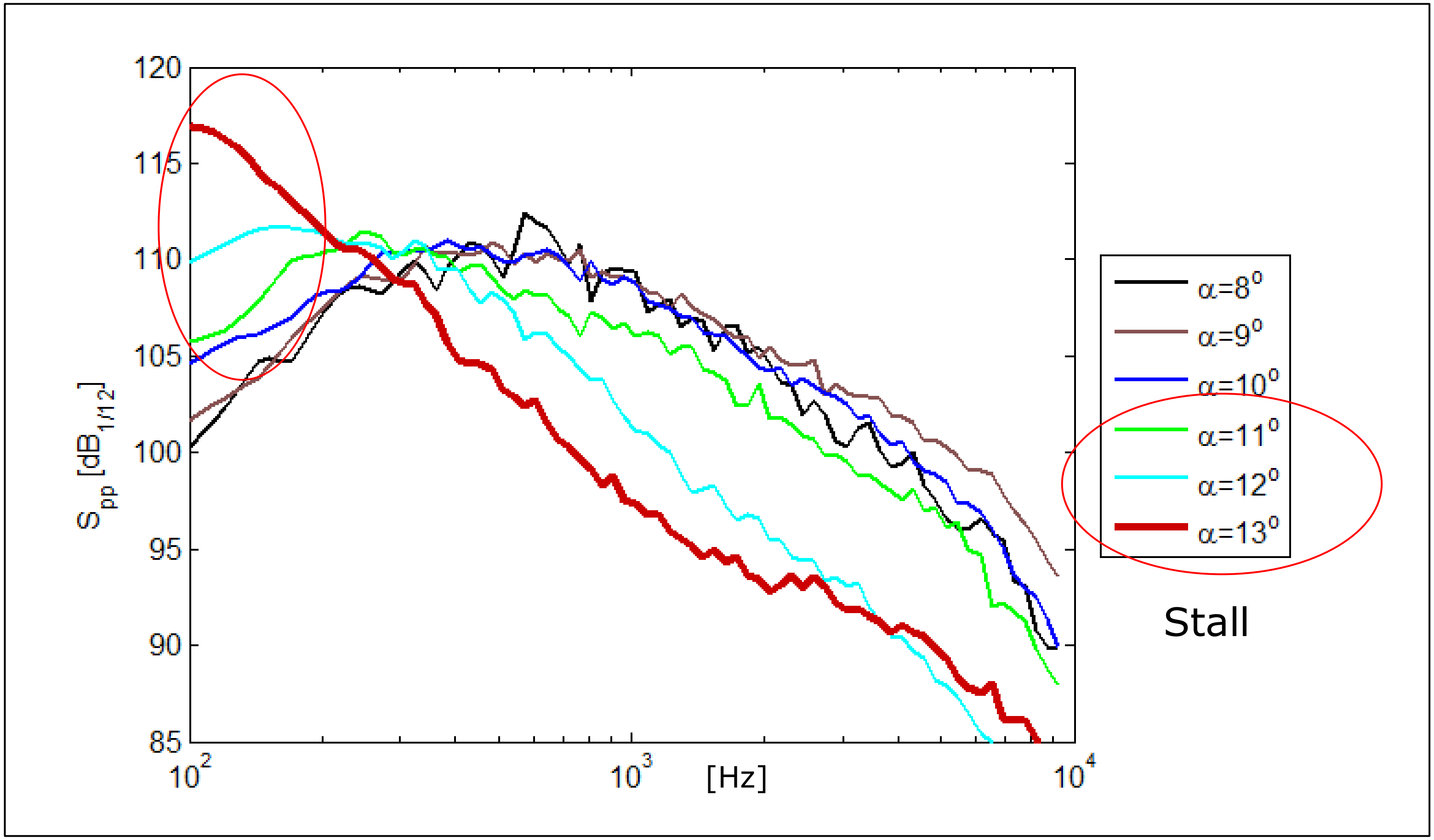


High 1p modulation **(15 dB)** at the low frequencies. Microphone close to the trailing edge

Strong wind shear causing variations of AOA reaching stall

DANAERO – NM80 turbine

- forced operation at high angle of attack by negative pitch and constant rpm

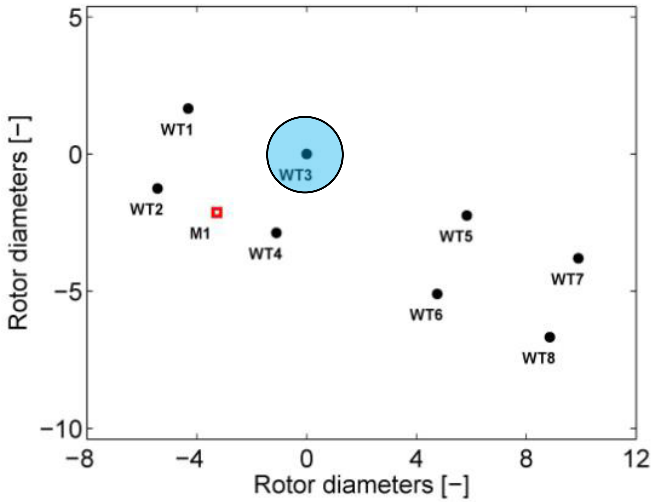


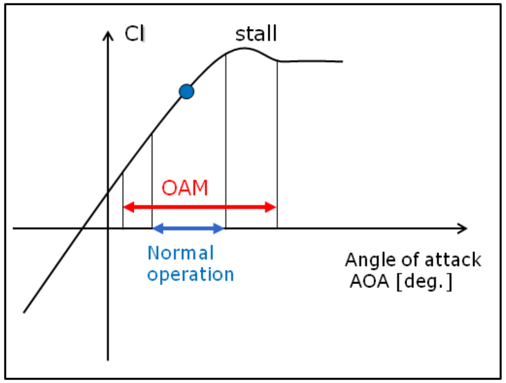
2. Measurement of inflow (AOA) on the rotating blade over three weeks on the same **turbine in 2003**

   - provides statistics on the occurrence of high angle of attack (stall) on a wind turbine in normal operation

2. Inflow measurements with one five hole pitot tube on same turbine – 2003

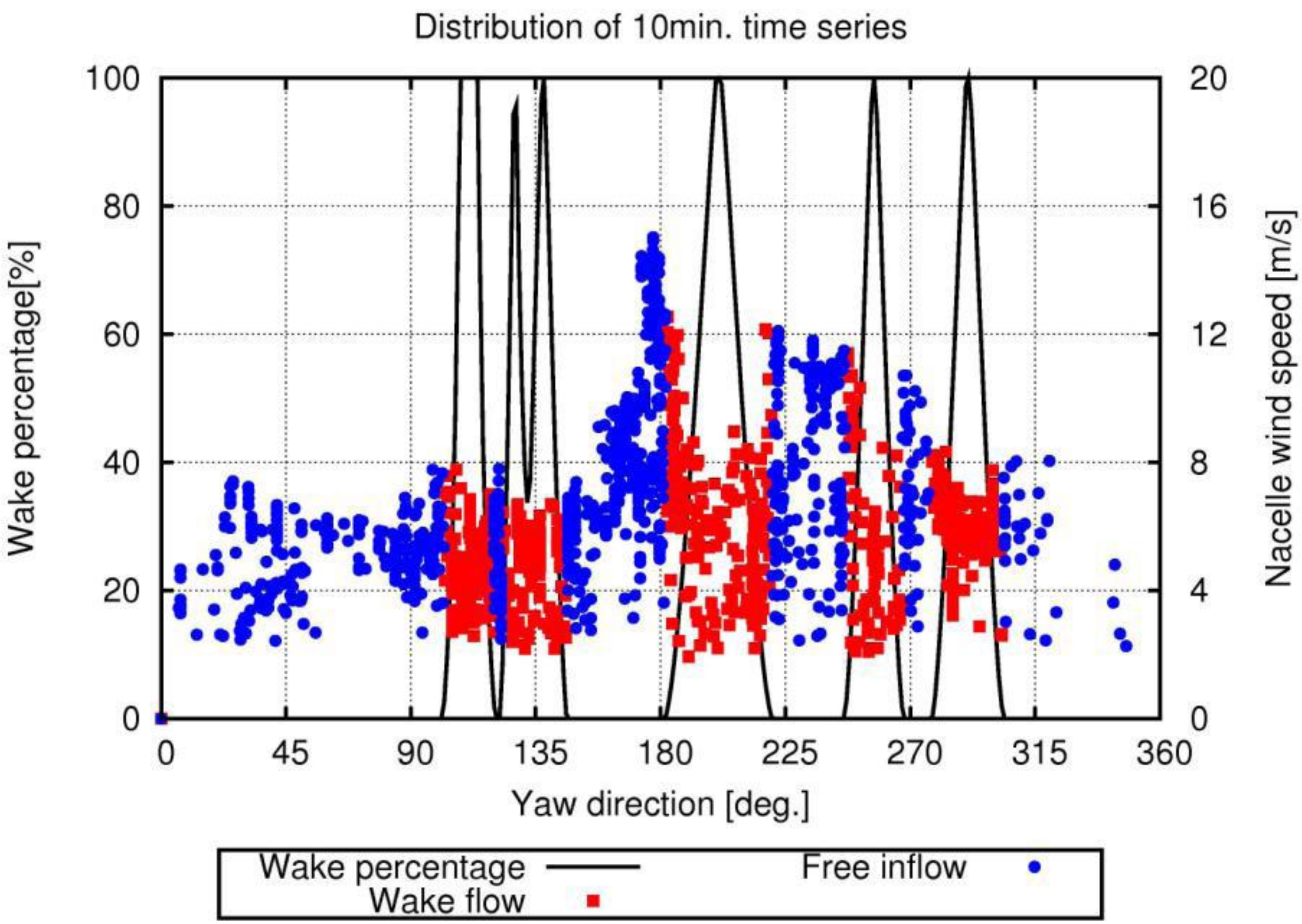
- 3 weeks with normal operation – basis for statistics of inflow (AOA)





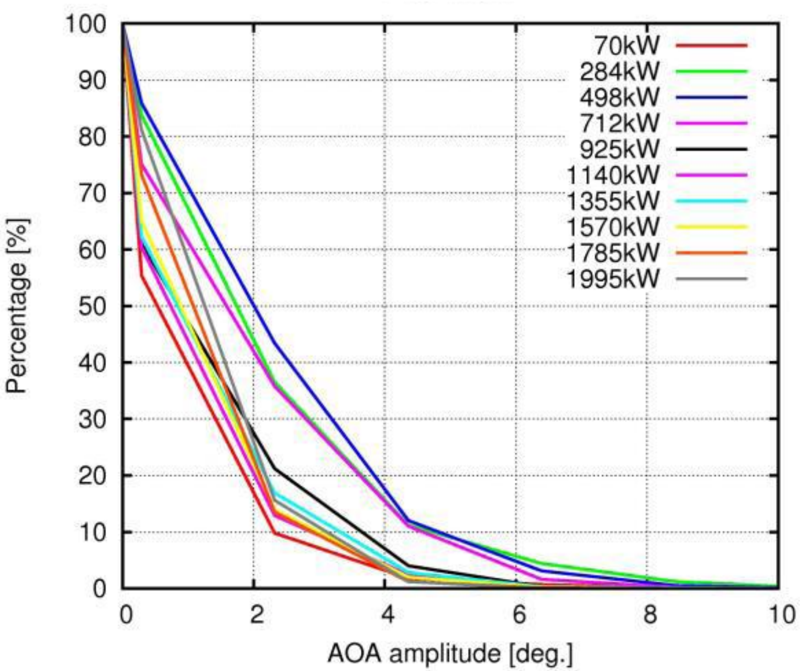
Turbine situated in a small wind farm with 8 turbines

Inflow measurements – 2003
- about 2000 of 10 min. time series

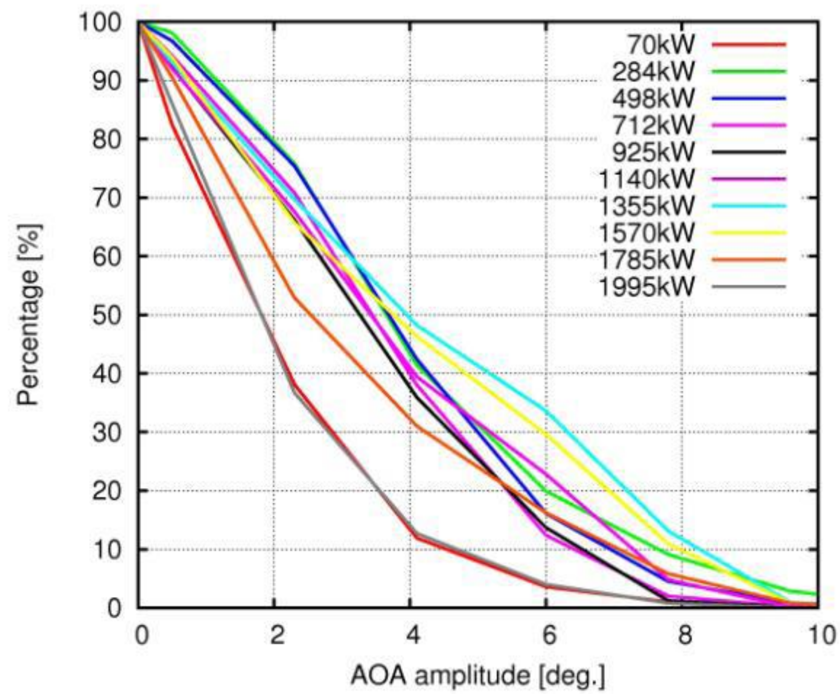


Inflow measurements – 2003
- analysis of about 2000 10 min. series

Free inflow



Wake operation



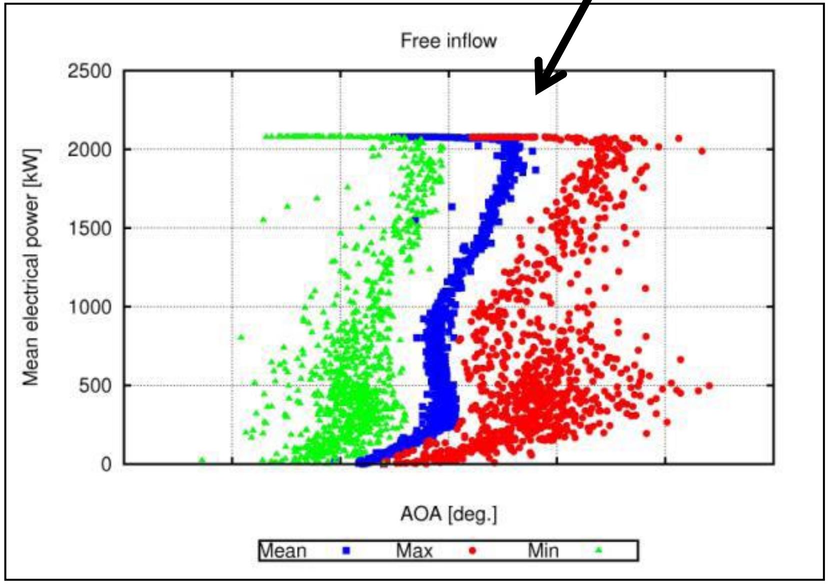
AOA amplitude is max to min

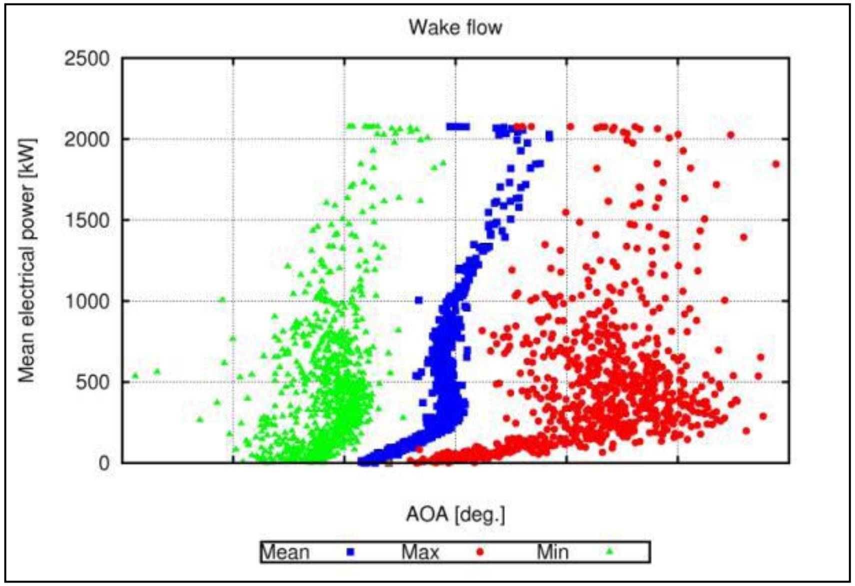
Madsen H Aa, Bertagnolio F, Fischer A, Bak C, Correlation of amplitude modulation to inflow characteristics. Proceedings of INTERNOISE 2014, Melbourne, Australia, November 16-19, 2014.

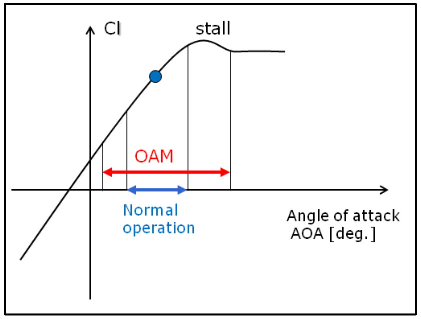
Inflow measurements - 2003

- 10 min. statistics of AOA variations - the risk of transient stall

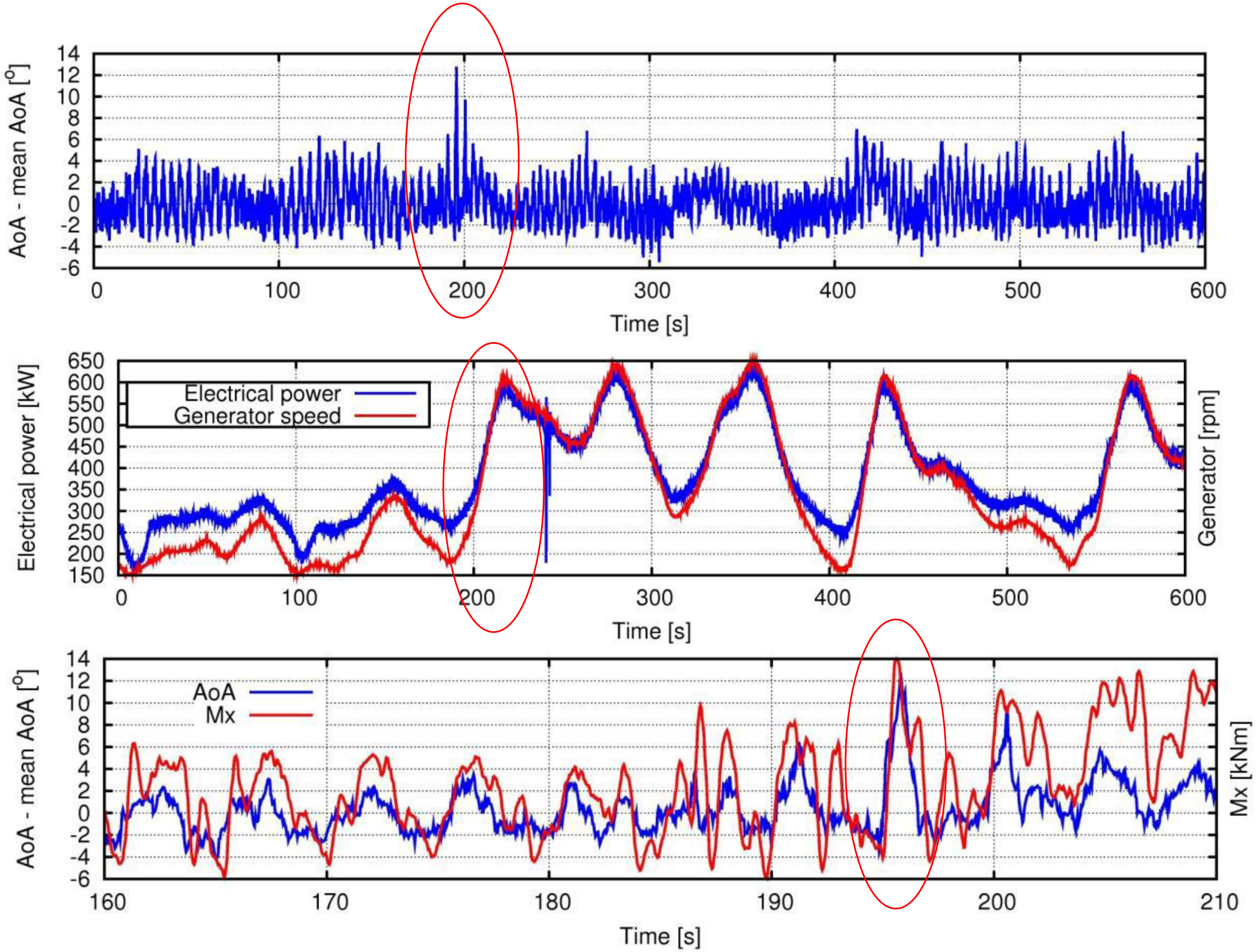
5 degrees between grid lines







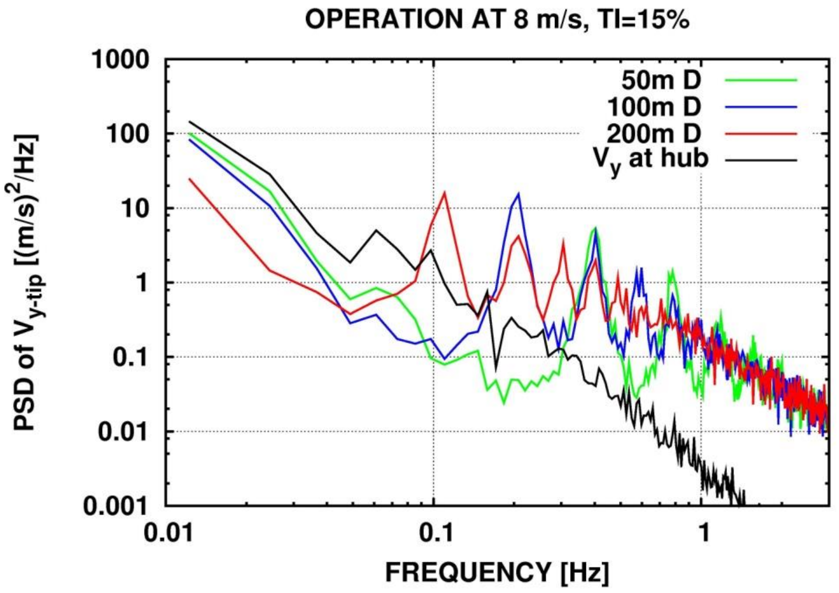
An example of high AOA

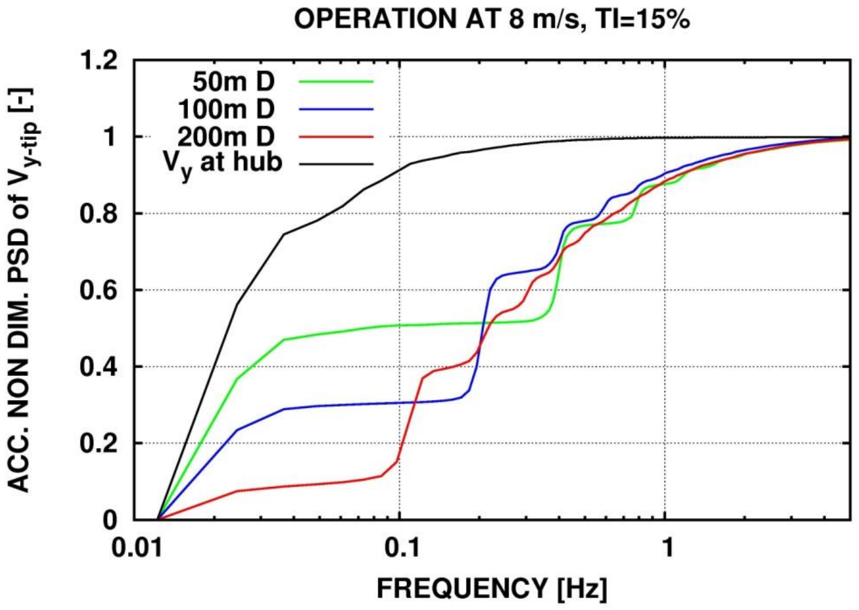


Mx is flapwise blade root moment

A scale effect due to rotational sampling of turbulence

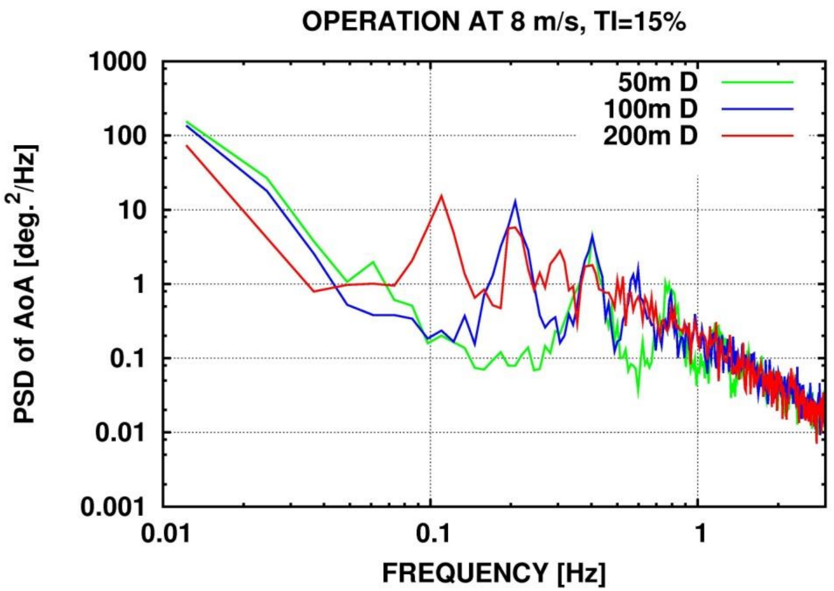
Spectrum of the wind seen from the tip of the rotating blade

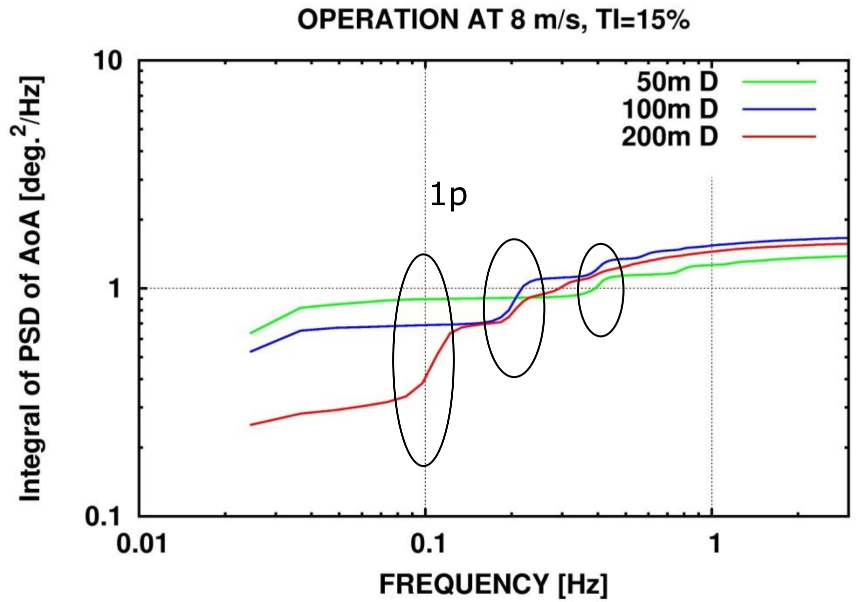




A scale effect due to rotational sampling of atmospheric turbulence

Increase in 1p content of AoA when upscaling rotors



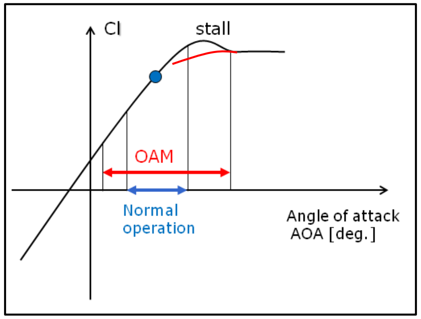


Blade leading edge roughness

NM80 turbine – DANAERO project

http://www.nacleanenergy.com/articles/17870/reliability-centered-maintenance-for-wind-turbine-blades

Leading edge rough-ness will decrease Clmax and increase risk for transient stall



Conclusions

- strong 1p modulation seen in measured SPF spectra on rotating 38m blade

- a shift in SPF spectra to lower frequencies when transient stall occurs

- very likely that trailing edge separation causing stall noise is a major mechanism of OAM

- wake and shear effects increase AoA variations

- transient stall seems closely linked to the variable speed operation of the turbine

- the intermittent character of the AoA variations corresponds well to observed characteristics of OAM

- upscaling of rotors will increase 1p AoA variations


Thank you for
your attention